Decarbonization of industrial processes using novel Sundial solar thermal units

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Abstract

The environmental impact of a novel solar thermal technology called Sundial that uses rotary Fresnel collectors is investigated. Two different designs were developed; one to be used for the metal processing industry located in a high latitude country and the other one for the dairy industry located in a low latitude country. In the metal processing industry, the Sundial replaces only the electricity while in the dairy industry, it replaces the use of fuel for heating and electricity for cooling. Environmental impact assessment of the Sundial units was conducted using SimaPro Software 9.2 and the results showed that the unit developed for the dairy industry had a higher environmental life cycle impact, which was related to the design of the unit containing more components and materials. A key advantage of the newly developed units is its ability to provide high temperatures for the requirements of the industrial processes like a metal processing industry. The carbon-dioxide emissions reductions for the potential application of the unit to the industrial process were also calculated for the both industries. It was projected that for the future capacity of the high latitude Sundial (HLS) of 1,828MWh, the GHG emissions reduction is 559.4 tonnes of CO_2 emissions while the future capacity of the low latitude Sundial (LLS) of 2,158 MWh, the GHG emissions reduction is 909.6 tonnes of CO_2 emissions. This demonstrates the great potential of the Sundial units to contribute to the decarbonization of industrial processes and meet the EU's 2050 environmental targets.

Keywords: decarbonization, solar thermal energy, rotary Fresnel collector, environmental LCA impact, industrial processes.

1. Introduction

Population growth, industrialisation and socio-economic development have increased energy demand globally (Achkari & El Fadar, 2020). Fossil fuels currently provide most of the world's energy needs, however, they are finite energy sources and increase greenhouse gas emissions into the atmosphere, resulting in global warming. Governments across the world are under pressure to reduce GHG emissions and to limit global warming to approximately 1.5°C due to the United Nations Framework Convention on Climate Change (UNFCCC) and 2015 Paris Agreements (UNFCCC, 2022). To meet these international climate change agreements, the EU Parliament and its member states have agreed to reduce carbon emissions by at least 55% by 2030, compared to 1990 levels and to be carbon-neutral by 2050 (European Commission, 2022). As a result, the EU has provided its member states with a number of incentives including the Just Transition Mechanism and the Innovation Fund (European Commission, 2022c) to encourage the reduction of GHG emissions leading to decarbonization of the industrial processes. The EU's Just Transition Mechanism offers funding for the transition of carbon-intensive industries to low carbon technologies (European Commission, 2022b). The Innovation Fund provides financial support for technologies that can achieve significant GHG emission reductions through low carbon technologies, renewable energy generation, and carbon capture (European Commission, 2022b).

In order to achieve the EU‘s environmental targets, the industrial sector which is the third largest consumer of energy in Europe is encouraged to implement renewable energy technologies such as solar thermal technologies and drastically reduce their use of fossil fuels (Eurostat, 2021). A large proportion of energy consumption in EU industry is for heating and cooling purposes where fossil-fuels are mostly used to provide thermal energy to industrial processes (Holler et al., 2021). Solar thermal technologies are well suited to provide temperatures of 100°C – 400°C in industries where non-concentrated solar collectors such as flat plate and evacuated tube collectors are used to provide low process temperatures up to 150°C and concentrated solar thermal technologies such as parabolic trough, linear Fresnel and rotary Fresnel collectors provide medium temperatures up to 400°C (Suman et al., 2015). The Sundial can provide temperatures up to 400°C for industrial processes, thereby accelerating the decarbonization of the industrial sector. It can also be used at both high and low latitudes, making it versatile to be used in industries at different locations.

The environmental impact of solar thermal technologies can be performed through life cycle assessment (LCA) using various methods such as Eco-indicator 99, ReCiPe indicator, and IMPACT 2002+. Life cycle assessment (LCA) is a technique used to quantify and evaluate the environmental impact of a product, process or service over its entire life cycle. It considers all activities from the extraction of raw materials, manufacturing, transportation, usage, to the final disposal or recycling of the products (Muthu, 2020). This technique has been commonly used for assessing the environmental impact of solar thermal plants and providing a holistic evaluation of the environmental performance of the plants. Several studies have investigated the environmental impact of the use of the solar thermal technologies such as parabolic trough and linear fresnel in different industries (Corona & San Miguel 2015; Dabwan et al., 2019; Gasa et al., 2021). However, it can be seen that the environmental impact of the rotary Fresnel collector is yet to be investigated. Therefore, this paper assesses the environmental performance of the Sundial solar thermal units which is a rotary Fresnel collector in order to understand its environmental impact.

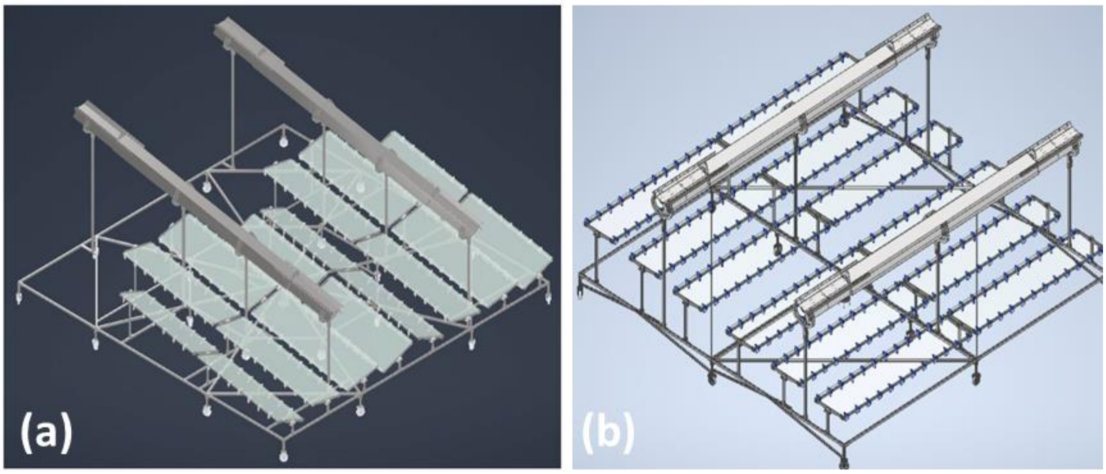
The aim of this study is to investigate the environmental impact of the HLS and LLS which can be used to provide thermal energy to different industrial processes. The environmental and human health impact of the components of the Sundial units are quantified. The components and processes with the highest impact are identified and recommendations are made to reduce the environmental impact. The greenhouse gas emissions reduction of using the Sundial to provide thermal energy to the processes of two industries is also presented.

1.1 Description of the Sundial solar thermal unit

The Sundial solar thermal unit can be used to provide high temperatures of up to 400°C of thermal energy to industrial processes. It is a novel solar thermal technology consisting of Fresnel solar collectors which simultaneously rotate around their longitudinal axis and reflect the solar beam radiation to two elevated receivers as the sun latitude changes, thereby heating up the thermal oil in its receiver tubes. The heated thermal oil will then flow to a thermal energy storage (TES) tank where the thermal energy is stored and released to the industrial processes when needed. The Sundial units will be implemented at two industrial sites; the first industry is a metal processing plant which is located in Romania at a high latitude of 47.1N. The second industry is a dairy factory located in Greece at a low latitude of 37.93N. The metal processing plant in Romania requires a high temperature of 220^{o}C while the dairy factory in Greece requires a lower temperature of 175^{o}C for their processes (ASTEP, 2019). The Sundial unit will also provide up to 135 kWh per day and 27 MWh of annual thermal energy for each end user (Ibarra et al., 2021).

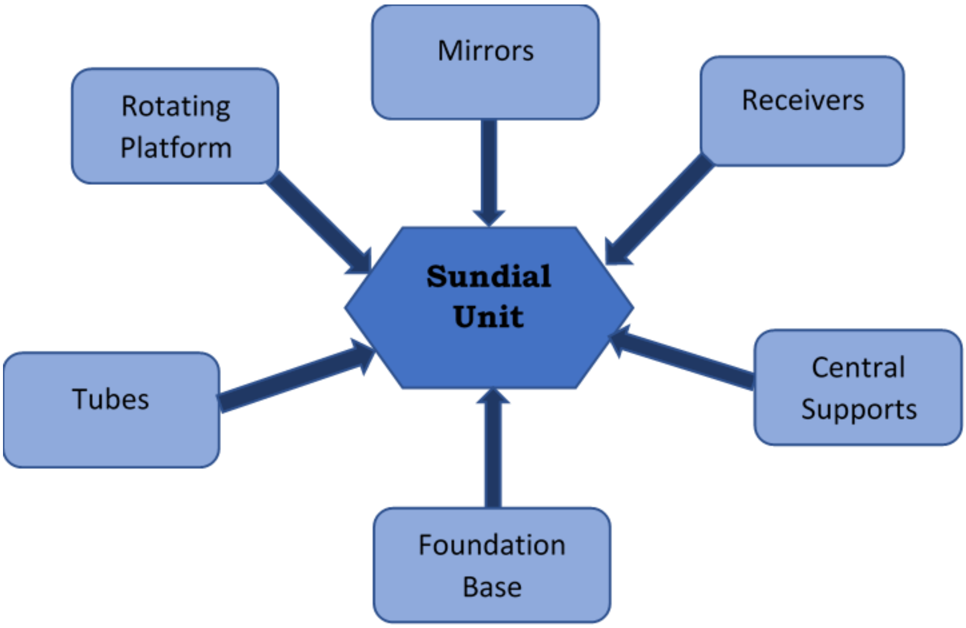
The design of the Sundial units for the two industries are different due to their varying locations and latitudes as depicted in Figure 1. The industry with a higher temperature requirement is located at a latitude of 47.1N with low irradiance throughout the year as the sun elevation varies due to the high latitude location. This requires the Sundial design to be specifically suited a lower mean sun altitude and a double-axis system to be used where, in addition to the platform rotating, the mirrors will also rotate to track the sun's varying elevation and capture more of the solar irradiance (Abbas et al., 2022). The design for the HLS is simpler and lighter due to the use of the two-axis tracking system. Furthermore, in order to minimise shading losses at such a high latitude, the mirror’s axes and receivers are located in two tilted planes as depicted in Figure 1b. In contrast, the industry with a lower temperature requirement is located at a latitude of 37.93N with high solar irradiance throughout the year as the sun is fixed at its culmination. Thus, a Sundial concentrator with a single-axis tracking system is used where only the platform rotates to capture solar irradiance. As seen in Figure 1a, the mirrors of the Sundial concentrator are shorter than the receivers and the lateral mirrors are shorter than the central mirrors inorder to reduce its end losses and increase its efficiency. The Sundial concentrator designed for the low latitude industry is also heavier than the one for the high latitude industry as it has 8 mirror lines compared to 6 for the high latitude industry (Abbas et al., 2022).

Figure 1: Design of Sundial Concentrators for (a) Low latitude industry (LLI) - 37.93N & (b) High latitude industry (HLI) – 47.1N (Abbas et al., 2022)



The main components of the Sundial units are presented in Figure 2. They consist of two semi-concentrators, each of them with its own receiver and mirror lines. The Sundial concentrator is divided into three main elements: the rotating platform, the mirrors and the receivers. The other components are the central supports for the rotating platform: the tubes that support the structure of the rotating platform and the foundation base upon which the rotating platform will be installed.

Figure 2: Main components of the Sundial Units



2. Methods

The environmental impact of the Sundial units was conducted using LCA's software SimaPro 9.2 (Pre-Sustainability, Netherlands) considering the raw materials extraction and processing, manufacturing of the components, transportation of the components from suppliers to end users and waste disposal of the components at the end of life stage. The system boundaries of the Sundial units are shown in Figure 3. Eco-Indicator 99 and Recipe indicator were the life cycle impact assessment methods used in this study. Data that include the type of materials, amount of materials, weight of the materials and processes used in manufacturing the Sundial for both end users; LLI and HLI were collected. The location of the suppliers of the components were considered and the transportation mileage from suppliers to the producer and producer to the end user was calculated. The life cycle inventory data for the Sundial was then placed in SimaPro where its environmental impact was assessed. The functional unit of the Sundial is 1 KWh of thermal energy. The estimated lifetime of the Sundial unit which is based on linear Fresnel technology is 30 years (Marugan-Cruz et al., 2019). The Sundial unit will provide up to 135 kWh per day and 25 MWh of annual thermal energy for each end user; LLI & HLI.

Life cycle assessment was conducted to quantify the environmental impacts of the Sundial which includes the extraction of the raw materials, transportation of materials & components, manufacturing of the components, assembly of the unit, operation and maintenance, and disposal of the components. This process is confirmed by studies that have conducted full LCA of solar thermal technologies (Whitaker et al., 2013; Gasa et al., 2021). The inputs are the energy and water consumed throughout the full life cycle of the Sundial units from extraction of raw materials to the disposal of the components. The outputs are the thermal energy generated, air and water emissions and any solid wastes produced throughout the life cycle of the Sundial units.

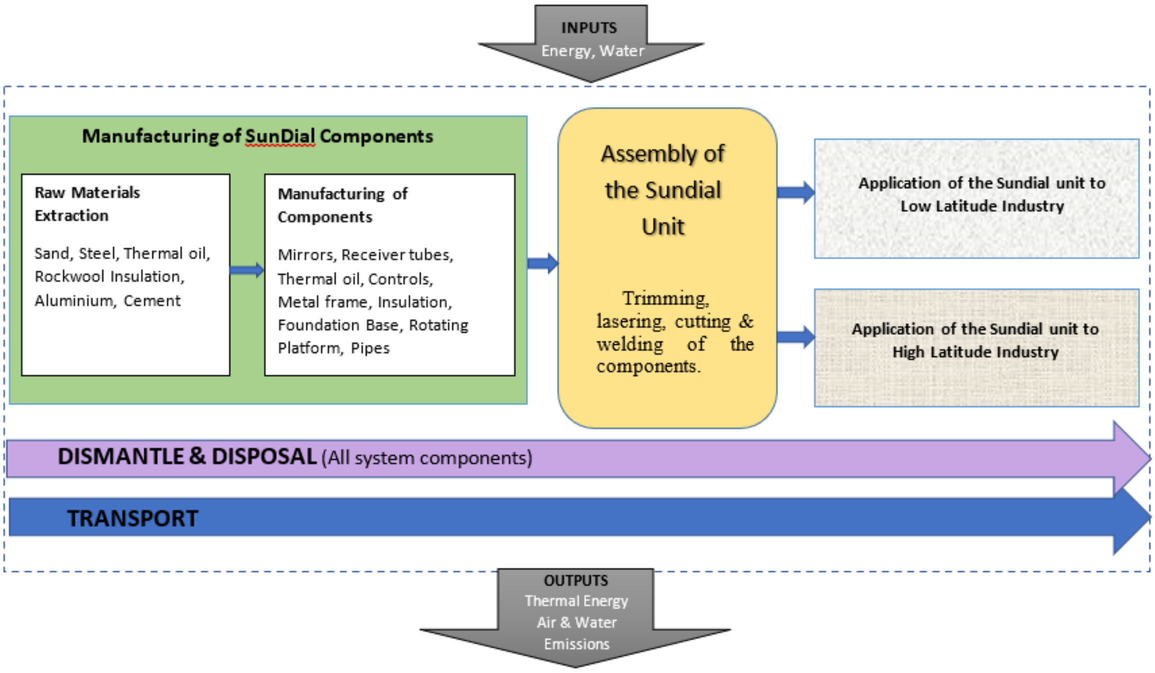
The current and future prospective GHG emissions reduction from the Sundials are presented in this study. The current GHG emissions reduction of the Sundials was calculated by using this formula: current capacity of Sundial multiplied by the carbon intensity per kwh for electricity/gas. The current annual capacity of the high latitude sundial (HLS) is 27.2 MWh, while the annual capacity of the low latitude sundial (LLS) is 27.4 MWh, obtained from Ibarra et al. (2021). The high latitude industry (HLI) is located in Romania and only uses electricity for its processes, therefore, the HLI's Sundial's current annual capacity of 27.2 MWh was multiplied with its carbon intensity of 0.306kgCO_2 per kwh for electricity in Romania to obtain its GHG emissions reduction of 8.3 tonnes of CO_2 emissions (RenSMART, 2022). The low latitude industry (LLI) which is in Greeece, uses liquid petroleum gas (LPG) for heating and electricity for cooling in their processes. It is estimated that half of the energy of the Sundial is used to provide heating and the other half used to provide cooling for LLI's processes. The carbon intensity for LPG is 0.22kg CO_2 per kwh and the carbon intensity for electricity is 0.623kgCO_2 per kwh for the LLI located in Greece (Engineering Toolbox, 2022; RenSMART, 2022). The carbon intensity of LPG and electricity were added together and then multiplied by 13.7 MWh (half of the LLI's Sundial's capacity of 27.4 MWh) to obtain its GHG emissions reduction of 11.5 tonnes of CO_2 emissions.

The current energy demand of the LLI is 3,597 MWh and the HLI is 3,046 MWh which were calculated from data provided by Nardini et al. (2020). The total energy demand for heating the metal pipes of the HLI was 846,000 MJ/year which was then converted to kwh by using this formula: 1 MJ = 0.2778 kwh (Nardini et al., 2020; UnitConverters, 2022). Therefore, HLI's energy demand is 846,000 MJ $\div$ 0.2778 = 3,046.4 MWh. To calculate the energy demand of the LLI's processes, its annual LPG and electricity consumption were added together. The LPG consumption of the LLI's processes is 118,601 m^3 (Nardini et al., 2020).

The following formula was used to convert the LPG (m^3) consumption into kwh: LPG (m^3) used $\times$ calorific value $\times$ correction factor (1.02264) $\div$ kwh conversion factor (3.6) = kwh (EonNext, 2022). The calorific value of LPG is 94MJ/m^3 (Momi et al., 2016). Therefore, the LPG consumption is (118,601m^3 $\times$94MJ/m^3 $\times$ 1.02264) $\div$ 3.6 = 3,166.9 MWh. The chiller uses electricity to cool the dairy products continuously for 24 hours a day throughout the year, therefore, the energy consumption of the chiller was calculated using this formula: power of chiller (50 kw) $\times 365\, days$ $\times$ 24 hrs = 430,000 kwh (430 MWh). The total energy consumption of the LLI is 3,166.9 MWh (LPG) + 430 MWh (electricity) = 3,597 MWh.

The future prospective GHG emissions reduction of the Sundials were calculated based on the Sundials providing 60% of the HLI and LLI's current energy demand, which resulted in 1,828 MWh for the HLI and 2,158 MWh for the LLI. The HLI uses only electricity for its processes. Therefore, the carbon intensity of electricity for the HLI which is 0.306kgCO_2 per kwh was multiplied by its prospective increased capacity of 1,828 MWh to obtain the GHG emissions reduction of 559.4 tonnes of CO_2 emissions when the Sundial is applied to the HLI's industrial processes (RenSMART, 2022). The LLI uses liquid petroleum gas (LPG) for heating and electricity for cooling in its processes. It is estimated that half of the energy of the Sundial is used to provide heating and the other half used to provide cooling for LLI's processes. Therefore, 1,079MWh of energy will be provided for the heating and 1,079 MWh of electricity provided for the cooling of the LLI's processes. The carbon intensity of LPG and electricity were added together and then multiplied by 1,079 MWh (half of the prospective increased capacity of 2,158 MWh) to obtain the GHG emissions reduction of 909.6 tonnes of CO_2 emissions when the Sundial is applied to the LLI's industrial processes.

Figure 3: System Boundary of the Sundial

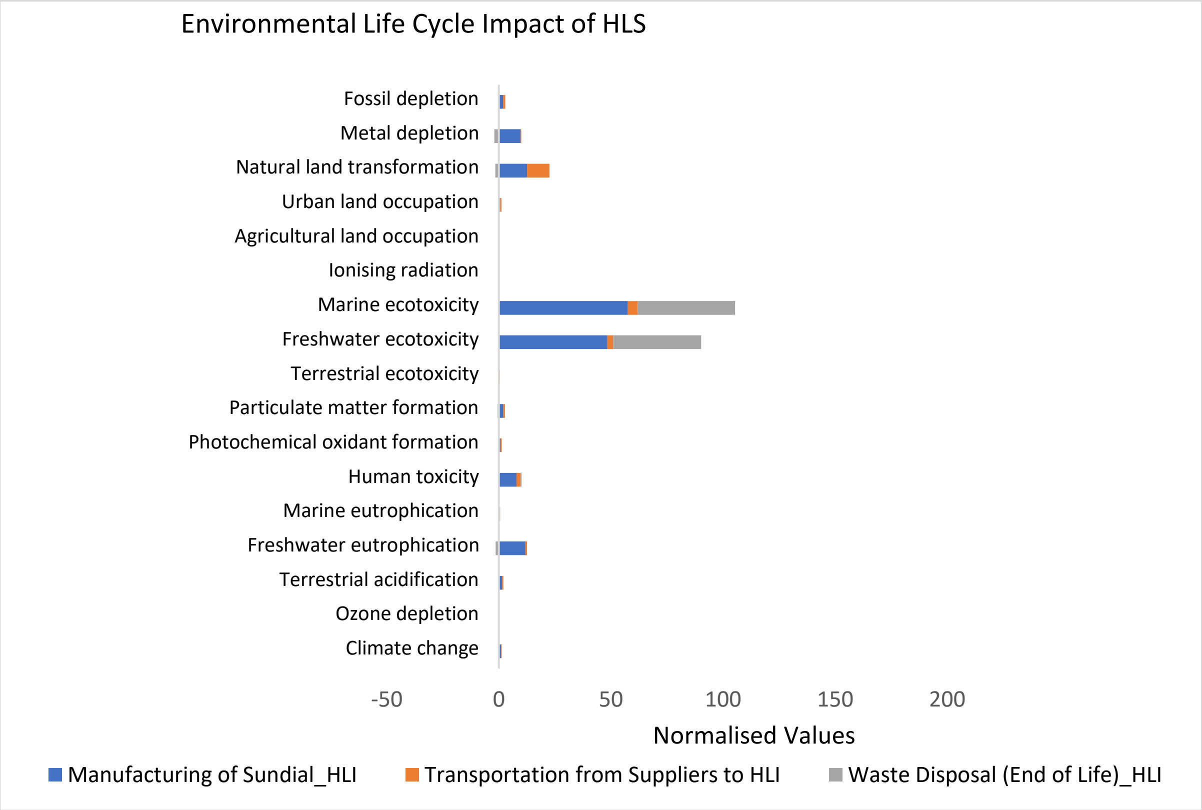


3. Results

Figure 4 shows the environmental impact of the Sundial units from the manufacturing of the components, transportation from suppliers to end users and waste disposal of the components at their end of life stage. The manufacturing phase of the Sundial units for both the LLI and HLI has the greatest environmental impact which is on marine and freshwater ecotoxicity, followed by natural land transformation, freshwater eutrophication, human toxicity, fossil and metal depletion. The manufacturing of the LLS demonstrated a larger environmental impact than for the HLS as depicted in Figure 4b, which can be attributed to the design of the unit using different components. The lowest environmental impact of the Sundial unit is on agricultural land occupation, ozone depletion, ionising radiation, terrestrial ecotoxicity and marine eutrophication. Overall, the manufacturing of both Sundial units has the biggest environmental impact, followed by the waste disposal of the Sundial components at their end of life stage, and then the transportation of the components from the suppliers to the end-users.

Figure 4: Environmental LCA impact of the Sundial Units (a) HLS (b)LLLS

(a)


Environmental Life Cycle Impact of HLS
Fossil depletion
Metal depletion
Natural land transformation
Urban land occupation
Agricultural land occupation
Ionising radiation
Marine ecotoxicity
Freshwater ecotoxicity
Terrestrial ecotoxicity
Particulate matter formation
Photochemical oxidant formation
Human toxicity
Marine eutrophication
Freshwater eutrophication
Terrestrial acidification
Ozone depletion
Climate change
-50
0
50
100
150
200
Normalised Values
Manufacturing of Sundial_HLI
Transportation from Suppliers to HLI
Waste Disposal (End of Life)_HLI

(b)

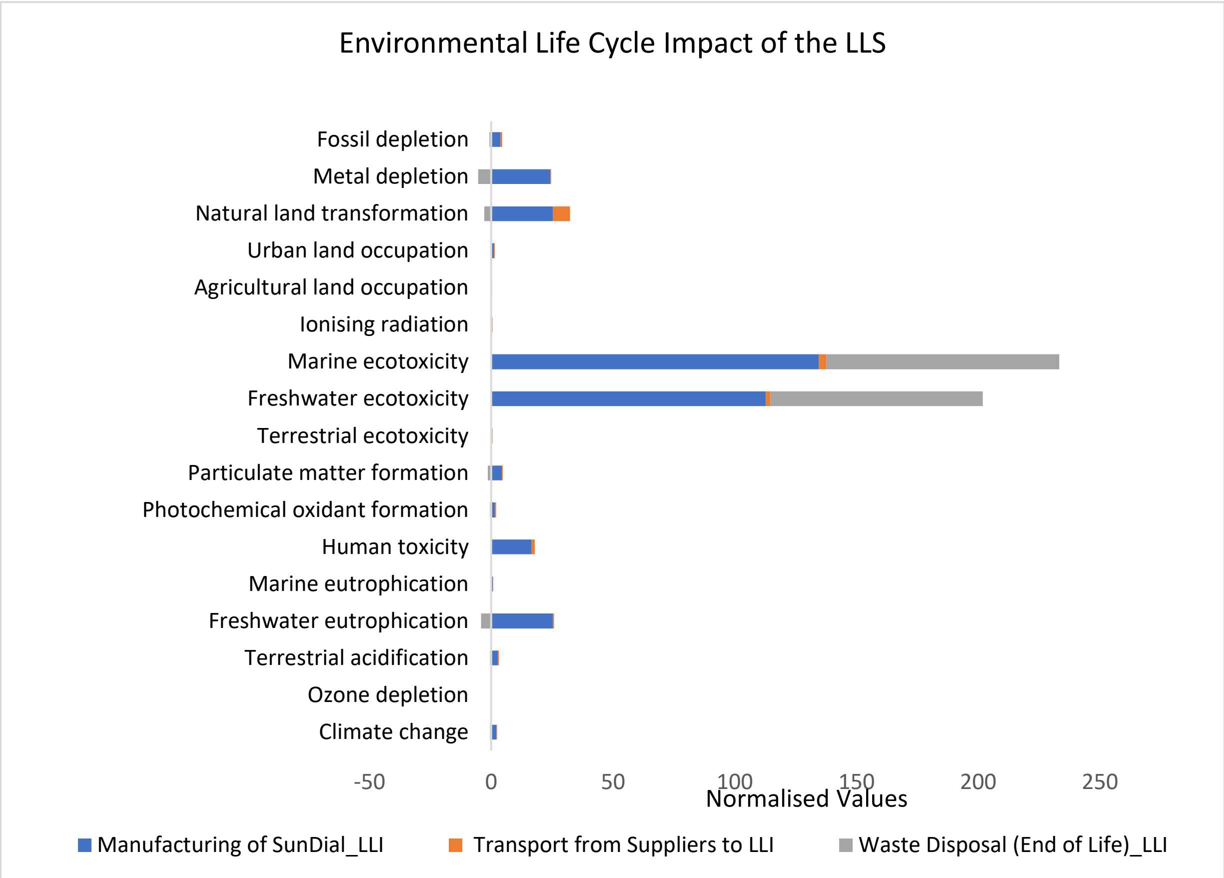


Figure 5 presents the human health, ecosystem, and resources impact of the components of the Sundial units. It was found that the LLS has a higher human health, ecosystem, and resources impact compared to the HLS for most of the components apart from the pipes. This can be attributed to the LLS having a larger number of elements such as more mirror lines, platform tubes and lateral supports which results in it having a heavier concentrator than that of the HLS. The component with the largest resources, ecosystem and human health impact is the rotating platform for LLS, followed by the receivers for both industries, the mirrors, rotating platform for the HLS, foundation base for the HLS, pipes and then the central support. As a result of the single-axis solar tracking system used for the LLS due to its low-latitude location, a different design was required for the LLS which resulted in a greater number of platform tubes and lateral supports being used than the HLS.

The rotating platform including the platform tubes comprised of a large amount of steel contributing to its significant human health, resources and ecosystem impact as depicted in Figure 5.

The substantial amount of aluminium used for the receivers and the amount of glass used for the mirrors resulted in their high human health and environmental impact. The foundation base is made of cement and has a lower impact than the mirrors, rotating platform and receivers of the Sundial units. A concrete foundation base was used for the HLS but not for the LLS as shown in Figure 5. The central supports which comprise of the support plates, bearing elevating & centring plates and central support bearing has the lowest impact due to the lower quantity of steel used in its production. The greatest impact of all the components of both Sundial units are on human health, followed by resources and then on ecosystem quality. This can be attributed to large amount of steel, aluminium and glass used in the manufacturing of the components of the Sundials.

Figure 5: Impact of Sundial Components on Human Health, Ecosystem Quality & Resources

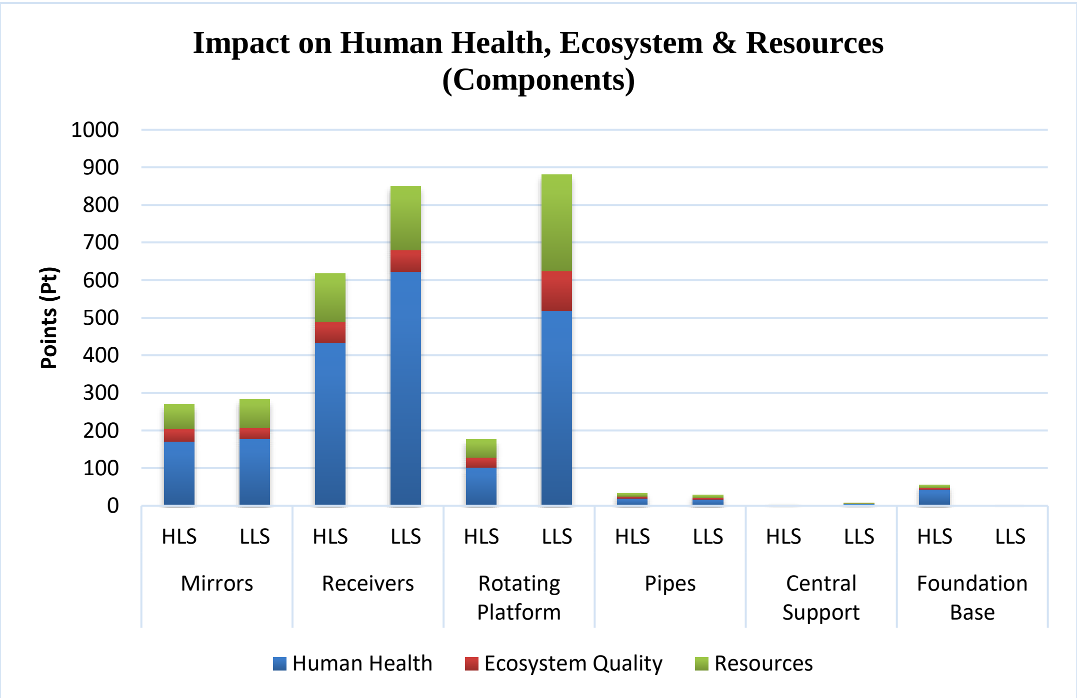
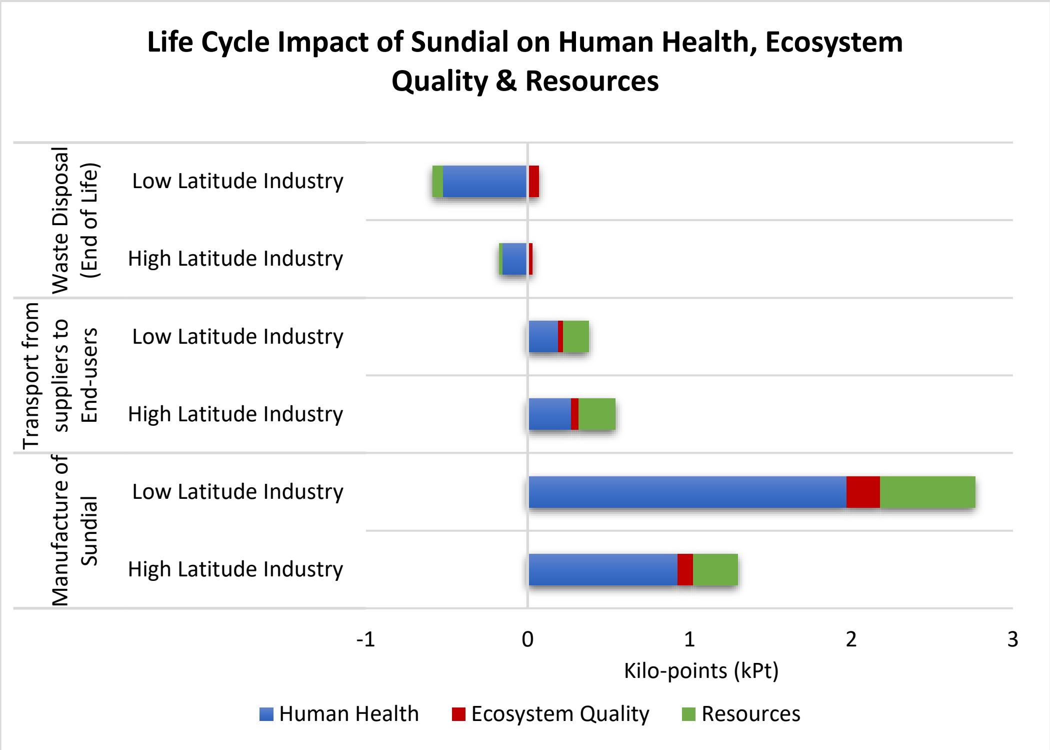


Figure 6 shows the total environmental LCA results of the Sundial units for both locations. It includes the environmental impact of the manufacturing of the components of the Sundial units, transportation of the components from the suppliers to the end users and waste disposal of the Sundial components at their end of life stage for both LLI and HLI. The LLS has a higher environmental impact than the HLS in the manufacturing phase which can be attributed to the different design used for both the HLS and LLS's concentrators because of their dissimilar locations and latitudes. A 2-axis solar tracking system was used in the design of the HLS because it is located at a high latitude, and this made its Sundial concentrator simpler and lighter than that of the LLS. The LLI is located at a lower latitude, thus a single-axis solar tracking system was used in the design of its Sundial concentrator. The different design of the Sundial concentrator for the LLI results in a larger number of mirror lines, 8 for the LLI compared to 6 for HLI as well as a larger number of platform tubes were required for the LLI's Sundial concentrator than that of the HLI. Furthermore, 20 lateral supports were required for the LLI's Sundial concentrator compared to only 10 lateral supports for the Sundial of the HLI. The higher number of components required for the LLS due to its unique design culminated in it using more materials than the HLS, which led to its higher human health, ecosystem quality and resources impact as shown in the manufacturing of the Sundial in Figure 6. The human health, ecosystem, and resources impact of the transportation phase for the HLI Sundial is higher than that of the LLI. This could be due to the greater distance to transport the Sundial components from the suppliers to the HLI in Romania. The waste disposal of the LLS at its end-of-life stage has a greater impact than that of the HLS. This can be attributed to the LLS having a higher number of components than the HLS, resulting in more components being disposed of at their end-of-life stage than the HLI Sundial.

Figure 6: Life Cycle Impact of the Sundial Unit on Human Health, Ecosystem Quality & Resources



Future Prospective GHG Emissions Reduction from the Sundials

Table 2 shows the current and future prospective capacity of both Sundials along with their GHG emissions reduction. The GHG emissions reduction is higher for the LLI than the HLI because the LLI which is based in Greece has double the carbon intensity of electricity at 0.623kgCO_2 per kwh than the HLI in Romania which has a carbon intensity of 0.306kgCO_2 per kwh (RenSMART, 2022). Futhermore, the LLI uses liquid petroleum gas (LPG) for heating and electricity for cooling in their industrial processes. Therefore, the carbon intensity of LPG and electricity is added together, increasing its total carbon intensity. This total carbon intensity of the LLI‘s LPG and electricity use is then multiplied with the capacity of the low latitude Sundial (LLS) which produces a higher GHG emission reduction savings than the high latitude sundial (HLS).

It can be seen in Table 2 that when the current capacity of the HLS is increased from 27.2 MWh to a future capacity of 1,828 MWh, its CO_2 emissions reduction rises from 8.3 tonnes to 559.4 tonnes of CO_2 emissions reduction. Likewise, when the current capacity of the LLS is increased from 27.4 MWh to a future capacity of 2,158 MWh, its CO_2 emissions reduction rises from 11.5 tonnes to 909.6 tonnes of CO_2 emissions. This demonstrates the potential GHG emissions reduction of the Sundial when it is used to provide thermal energy to industries at large capacities.

Table 2: Future Prospective Capacity & GHG emissions reduction of the Sundials

	High Latitude Sundial		**Low Latitude Sundial**	
Units	Current Capacity	Future Prospective Capacity	Current Capacity	Future Prospective Capacity
Energy provided (MWh/year)	27.2	1,828	27.4	2158
GHG Emissions reduction	8.3 tonnes of CO_2 emissions	559.4 tonnes of CO_2 emission	11.5 tonnes of CO_2 emissions	909.6 tonnes of CO_2 emissions

4 Discussion

The factors that impact on the environmental performance of a solar thermal plant includes its components and its life cycle phases. This study found that the manufacturing of the Sundial units had the highest environmental impact, followed by waste disposal of the components at their end of life stage and then the transportation of the components from the suppliers to the end users. This is corroborated by Burkhardt et al. (2011) and Klein & Rubin (2013) who found that the manufacturing phase of a solar thermal plant had the greatest environmental impact which can be attributed to the large amount of energy used in the manufacturing of the components. The disposal phase had a lower impact which could be due to less energy required in the disposal of the components. Some of the components may also be recycled or re-used which reduces its environmental impact. Studies have reported that the manufacturing of the solar field components such as mirrors and frames contributes the largest GHG emissions of the manufacturing phase of a solar thermal plant (Klein & Rubin 2013; Whitaker et al., 2013;

Pelay et al., 2020). This study found that the rotating platform, receivers and mirrors had the greatest environmental impact which can be attributed to the significant amount of steel used for rotating platform, aluminium used for the receivers and the amount of glass used for the mirrors of the Sundial units. This is confirmed by Pelay et al. (2020) who state that the solar field comprises of metals and mirrors and most of their emissions are due to the extraction, transformation and shaping of these materials.

The Sundial unit has the potential to achieve significant GHG emissions reduction when it provides thermal energy to industrial processes in large capacities. The Sundial currently provides 27.2 MWh and 27.4MWh of thermal energy to the processes of the HLI and LLI, respectively. The annual energy demand for the LLI is 3,597 MWh while the annual energy demand for the HLI is 3,046 MWh. A saving of 11.5 tonnes of CO_2 emissions is achieved when the Sundial is used to provide heat to the processes of the low latitude industry. A saving of 8.3 tonnes of CO_2 emissions is achieved when the Sundial is applied to the HLI which uses only electricity for its processes. However, when the capacity of the Sundial is increased to 1,828 MWh for the HLI and 2,158 MWh for LLI, annual CO_2 emissions reduction of 559.4 tonnes and 909.6 tonnes are achieved for the HLI and LLI, respectively. This demonstrates the great potential of the Sundial to reduce CO_2 emissions when applied to industries in a large capacity.

Furthermore, the Sundial can reduce costs for industries as companies are required to purchase a permit for each tonne of CO_2 they emit through the EU's Emissions Trading System (European Parliament, 2022). The Sundial which is a renewable energy technology can be used to avoid these additional costs for industries. To meet the EU's 2030 climate and energy framework targets to reduce GHG emissions by at least 40% from 1990 levels and to increase the share of renewable energy to 32% (European Commission, 2022b), solar thermal technologies such as the Sundial can be used in the decarbonization of industries.

5 Conclusion

This study investigated the environmental and human health impact of a Sundial solar thermal units for two end-users; a low temperature and a high latitude industry. The study also highlighted the technical, economic, and environmental benefits of using the Sundial units to provide thermal energy in industries. The factors that impact on the environmental performance of a solar thermal plant including its components and its life cycle phases were also discussed. It was found that the manufacturing of the Sundial units had the largest environmental impact, followed by transportation of the components from the suppliers to the end users and then the waste disposal of the components at their end-of-life stage. This was corroborated by other studies that reported a similar pattern of results. This study found that the rotating platform and the receivers had the greatest environmental impact which can be attributed to the large amount of steel and aluminium used for the rotating platforms and receivers, respectively. This was confirmed by other studies who reported the solar field components like the receivers, platform structures and mirrors as having the highest environmental impact of a solar thermal technology.

Manufacturing of the Sundial components demonstrated the greatest impact on human health, followed by resources and then on ecosystem quality. This can be attributed to the large amount of metals (steel and aluminium) used in the manufacturing of the Sundial components, particularly for the rotating platforms and receivers. In order to reduce the human health and environmental impact of manufacturing the Sundials, recycled metals could be used in the future to produce the Sundials' components. The Sundial reduces GHG emissions when its applied to the industrial processes of the two industries. The use of the Sundial units in industries provides environmental, technical, and economic benefits. Its technical benefits include the ability to provide temperatures up to at 400°C for industrial processes at locations of low and high latitudes where other solar thermal technologies may be limited to operate. As a result of its double-axis solar tracking system, the Sundial units can be used at locations of high latitudes, whilst its single-axis solar tracking system enables the unit to also be used at locations of low latitude. In addition, the Sundial is a renewable energy technology that can save industries money from rising energy costs as well as from purchasing permits for the amount of CO_2 emitted as required by the EU's Emissions Trading System. The Sundial can also contribute to the decarbonisation of industries when applied in large capacities to their processes.

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